Archeological and pedological evidence for large prehistoric earthquakes in the New Madrid seismic zone, central United States

Martitia P. Tuttle Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, and Department of Geology, University of Maryland, College Park, Maryland 20742

Eugene S. Schweig U.S. Geological Survey and Center for Earthquake Research and Information, University of Memphis, Memphis, Tennessee 38152

ABSTRACT

Prehistoric liquefaction features have been identified by careful observation of their structural and stratigraphic relations to Native American occupation horizons and their subtle soil characteristics. The ages of these liquefaction features have been estimated from radiocarbon dating of wood associated with the features and Native American artifacts found within bounding occupation horizons. At three sites near Blytheville, Arkansas, in the central part of the New Madrid seismic zone, one sand-blow crater formed between A.D. 800 and 1400, two sand-blow deposits formed between A.D. 800 and 1670, and three, possibly four, sand dikes formed since 4035 B.C. Where not found in association with Native American occupation horizons and artifacts, prehistoric liquefaction features can be difficult to distinguish from features that formed during the great New Madrid earthquakes of A.D. 1811 and 1812. This raises the possibility that prehistoric liquefaction features may have been misinterpreted during previous studies in the area. Nevertheless, a paleoearthquake chronology is beginning to emerge for the New Madrid seismic zone. Our findings are consistent with paleoseismological studies in the northern part of the seismic zone and suggest a recurrence interval of hundreds of years for earthquakes large enough to induce liquefaction in this region (M ≥ 6.4). By mapping the age distribution of liquefaction features, a more accurate assessment of the long-term earthquake potential of the region will be possible.

INTRODUCTION

The New Madrid seismic zone, which spans southeastern Missouri, northeastern Arkansas, northwestern Tennessee, southeastern Kentucky, and southern Illinois, is the most seismically active area in North America east of the Rocky Mountains. This seismic zone was the source area of three great earthquakes of moment magnitude M ≥ 8 in A.D. 1811 and 1812, inferred to be among the largest known intraplate earthquakes (Johnston and Kanter, 1990). The 1811 and 1812 New Madrid earthquakes caused severe liquefaction over a broad region (Fig. 1; Fuller, 1912; Obermeier, 1989).

The New Madrid seismic zone is in the northern part of the Mississippi embayment, a broad trough of Late Cretaceous and younger sedimentary deposits that broadens to the south-southwest and the axis of which coincides approximately with the Mississippi River (Buschbach and Schwalb, 1984). Late Quaternary sediments within the embayment are predominantly Pleistocene braided-stream deposits and Holocene meander-belt and backswamp deposits of the Mississippi, St. Francis, and Little Rivers (Saucier, 1974; Guccione et al., 1990). In general, these Quaternary deposits are only moderately susceptible to liquefaction and are not likely to liquefy unless shaken by an earthquake of M ≥ 6.4 (Obermeier, 1989). Although the New Madrid seismic zone is very complex in detail, it is presumably the result of east-northeast–directed compression and reactivation of structures associated with the Reelfoot rift (Zoback and Zoback, 1989).

Geophysical and geologic studies in the region over the past decade have provided estimates of recurrence intervals of large-magnitude earthquakes ranging from several hundreds of years to >10 ka. The frequency and magnitude of modern seismicity suggest that events of M ≥ 8.0 should occur every 550 to 1100 yr (Johnston and Nava, 1985). Liu et al. (1992) reoccupied a 1950s triangulation network in the southern New Madrid seismic zone using the Global Positioning System and found unexpectedly rapid accumulation of crustal shear strain on the order of 10^{-7}/yr. Their data indicate that sufficient strain energy to produce an event the size of the 1811 earthquake could accumulate in 400 to 1100 yr (Schweig and Ellis, 1994). Most results from paleoseismological investigations agree with this estimate.

Russ (1982) was the first to recognize that large prehistoric earthquakes that induced liquefaction had occurred in the New Madrid seismic zone. On the basis of structural relations and radiocarbon dating of liquefaction features, normal faults, and a monoclinal fold in Holocene sediments at the Reelfoot scarp (Fig. 1), Russ (1982) determined that three earthquakes (including the 1811 and 1812 sequence) had occurred in the past 2000 yr. This suggested that earthquakes of body-wave magnitude m_b ≥ 6.2 (or M ≥ 6.4, a reasonable minimum magnitude likely to cause lique-

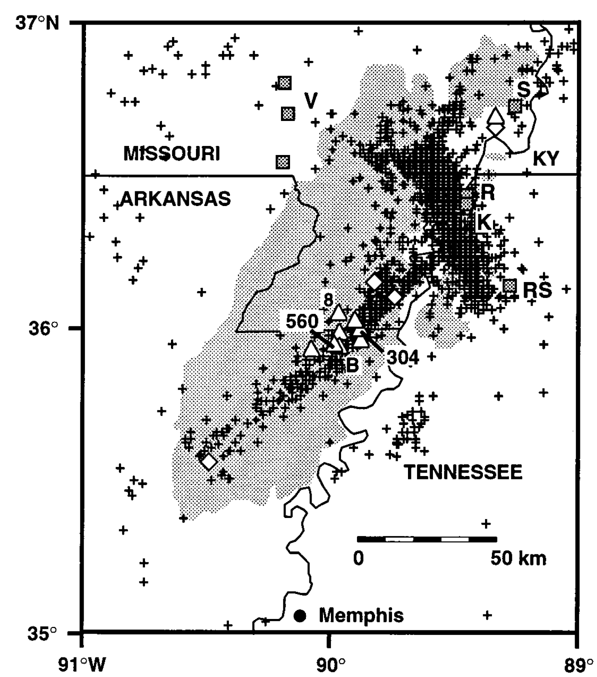

Figure 1. Map of most of New Madrid seismic zone (excluding southern Illinois). Shading represents >1% of area covered by sand-blow deposits (Obermeier, 1989). Crosses indicate locations of recent (A.D. 1974–1991) seismicity. Gray squares indicate sites of other paleoseismic studies referred to in text: R = Russ (1982), K = Kelson et al. (1994), RS = Rodbell and Schweig (1993), S = Saucier (1991), and V = Vaughn (1991). B represents location of Blytheville, Arkansas. White triangles indicate sites of paleoliquefaction features; 304 = Yarbro-304, 560 = Eaker-560, and 8 = Main-8. White diamonds denote sites where investigations are scheduled for late in 1994.

faction and surface faulting) recur about every 600 yr. The Reelfoot scarp was reexcavated by Kelson et al. (1994), who found evidence of four events (including the 1811 and 1812 sequence) in the past 2400 yr, which suggests a 400 to 1200 yr average recurrence interval. Liquefaction features at Towosahgy archeological site, located ~30 km northeast of Reelfoot Lake (Fig. 1), are thought to be the result of two large prehistoric earthquakes within the past 1500 yr (Saucier, 1991). Empirical relations between earthquake magnitude and maximum distance from the source of significant liquefaction (e.g., Youd and Perkins, 1987) provide a conservative estimate of $m_b \geq 6.2$ (Saucier, 1991) as the minimum magnitude earthquake that could be responsible for liquefaction at both Towosahgy and Reelfoot scarp. Vaughn (1991) identified liquefaction features west of the New Madrid seismic zone (Fig. 1) that he attributed to three prehistoric events, the times of which are not well constrained.

In contrast, similar interpretations of liquefaction features have not been made south of Reelfoot scarp. Wesnousky and Leffler (1992) found no unequivocal evidence of Holocene paleoliquefaction, despite reconnaissance of tens of kilometres of drainage ditches and documentation of numerous liquefaction features (Fig. 1). They concluded that earthquakes similar in size to the great New Madrid earthquakes of 1811 and 1812 may have a recurrence interval of at least 5 to 10 ka. Similarly, Rodbell and Schweig (1993) interpreted sand blows on alluvial terraces, thought to be 10 to 20 ka in age, along the Obion River in Tennessee (Fig. 1) as resulting from the 1811 and 1812 New Madrid earthquakes.

A credible determination of the rate of occurrence and spatial distribution of large-magnitude earthquakes is critical for realistic earthquake hazard assessment. Several paleoseismological studies are currently underway in the region, the goals of which are to resolve the question of recurrence interval of large prehistoric earthquakes. This paper presents results from one such study that has identified prehistoric liquefaction features near Blytheville, Arkansas, where liquefaction-related features were previously interpreted as the result of the 1811 and 1812 earthquakes. Our age estimates of liquefaction features support a short recurrence interval for large-magnitude earthquakes in the New Madrid seismic zone.

RECONNAISSANCE AND SITE INVESTIGATIONS

An ongoing search for prehistoric liquefaction features includes reconnaissance of topographically elevated ground characterized by mature soils (e.g., Amagon, Dundee, and Routon soil series) and Native American occupation as well as recently cleaned or enlarged drainage ditches (maintained by the U.S. Army Corps of Engineers) located in low-lying areas. We selected 14 sites for detailed investigation in southeastern Missouri and northeastern Arkansas (Fig. 1). To date, investigations are complete for 10 sites and are planned for another four sites in the autumn of 1994. In this paper, we present results from three study sites, all located within 15 km of Blytheville, Arkansas. The three sites occur within Holocene meander-belt and backswamp deposits of the Mississippi and Little Rivers (Guccione et al., 1990). Yarbro-304 and Eaker-560 are located on higher ground that had been occupied by Native Americans, whereas Main-8 is exposed along Main Ditch. Stratigraphic relations of liquefaction features and Native American occupation horizons and features, in the first two cases, and crosscutting relations and soil development of multiple liquefaction features, in the third case, led us to think that these features were prehistoric and warranted additional scrutiny.

Liquefaction Features at Site Yarbro-304

At Yarbro-304 (Fig. 1), ~6 km north of Blytheville, a large sand-blow crater and associated feeder dike crosscut a thick Native American occupation horizon (Fig. 2). This horizon is a silt loam that contains many artifacts, including potsherds, pieces of fired clay, and a stone chisel. The feeder dike of the sand-blow crater is filled with medium- to coarse-grained sand that is single grained and has a loose consistency. The 3-m-long, 2-m-wide, 2-m-deep sand-blow crater is filled with loamy sand that contains several potsherds. A Native American pit is in the upper part of the sand-blow crater. The pit is filled with a sandy loam (along the base) and silt loam and contains ceramic artifacts and charcoal.

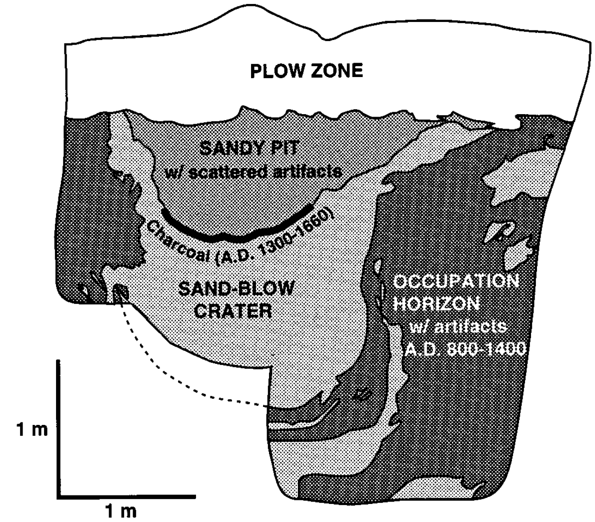

Figure 2. Log of trench wall at Yarbro-304, ~6 km north of Blytheville, Arkansas. Prehistoric sand-blow crater crosscuts thick Native American occupation horizon containing artifacts. Feeder dike below crater not shown. In addition, pit containing artifacts and charcoal was dug into top of sand-blow crater. This sand-blow crater formed between A.D. 800 and 1400.

The ceramic artifacts in both the occupation horizon and the pit within the sand-blow crater include Varney Red Filmed pottery, which is a regional marker for the early (A.D. 800 to 1200) to middle (A.D. 1200 to 1400) Mississippian cultural periods (Tuttle et al., 1993). Radiocarbon dating of charcoal from the base of the pit yielded a carbon-13 adjusted age of 455 ± 110 yr B.P. (Geochron-19080). On the basis of the Pretoria calibration procedure (Vogel et al., 1993), this corresponds with a 1σ (68% probability) calibrated age range of A.D. 1405 to 1515 or 1580 to 1625 (2σ range, 95% probability, of 1300 to 1660). Although most of our 2σ calibrated age ranges include modern dates, they can be reasonably excluded given the archeological contexts of the samples.

The crosscutting relation between the sand-blow crater and the early to middle Mississippian occupation horizon indicates that liquefaction occurred sometime after A.D. 800. The pit dug into the top of the sand-blow crater indicates that the site was reoccupied after the liquefaction event. Radiocarbon dating of charcoal in the base of the pit suggests that it was excavated after A.D. 1300. Potsherds within the pit indicate that the liquefaction event occurred before the close of the middle Mississippian cultural period. Therefore, the sand-blow crater formed between A.D. 800 and 1400.

Liquefaction Features at Site Eaker-560

Eaker-560 (Fig. 1) is located on Eaker Air Force Base ~4 km northwest of Blytheville and was first brought to our attention by R. Lafferty (Schweig et al., 1993). At this site, two stacked sand blows are found between occupation horizons containing Native American artifacts (Fig. 3).

The upper sand blow is composed of a fine sand and shows some signs of soil development including weak, very fine, angular blocky structure and very friable consistency. The lower sand blow

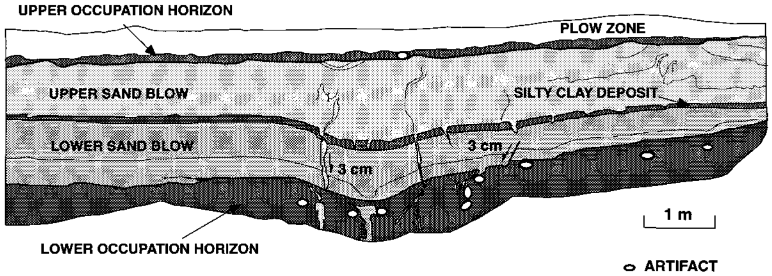

Figure 3. Log of trench wall at Eaker-560, ~4 km northwest of Blytheville, Arkansas. Two stacked sand blows are found between Native American occupation horizons. Lower sand blow contains two fining-upward sequences. Fine line indicates contact between these. Within upper sand blow, fine lines show flow structure. These sand blows formed between A.D. 800 and 1640.

is composed of two fining-upward sequences, which may represent cyclic pore-pressure increases during an earthquake. The lower sequence consists of a medium to fine sand and appears to be unaffected by soil-forming processes. The upper sequence is a fine to very fine sand that exhibits soil development characterized by weak to moderate, very fine, angular blocky structure and very friable consistency. Both sand blows contain flow structure and clasts of underlying horizons. The two sand blows are separated by a 10-cm-thick silty clay layer that pinches out toward the margin of the sand blow. The silty clay layer and underlying sand blow are crosscut by two feeder dikes of the upper sand blow. The block between the two feeder dikes is dropped down by ~3 cm.

The 10-cm-thick upper occupation horizon overlies the upper sand blow and is a sandy loam that contains artifacts of the late Mississippian culture (A.D. 1400 to 1670). In addition, pits (outside area shown in Fig. 3) are present in the top of the underlying sand blow. Charcoal from tree roots grown into one such pit yielded radiocarbon ages of 300 ± 60 (Beta-69618) and 240 ± 60 (Beta-69617) yr B.P., which correspond to 1σ calibrated age ranges of A.D. 1510 to 1660 (2σ range of A.D. 1460 to 1680, 1770 to 1800, or 1940 to 1955) and A.D. 1640 to 1680 or 1770 to 1800 (2σ range of A.D. 1510 to 1600, 1620 to 1700, 1720 to 1820, 1850 to 1860, or 1920 to 1955), respectively. The lower occupation horizon is buried beneath the two sand blows and is a silty loam to silty clay loam that contains many artifacts of late Woodland (A.D. 500 to 800) and early Mississippian (A.D. 800 to 1200) cultures. The transition period between the two cultures was around A.D. 800 (Morse and Morse, 1983).

The silty clay layer, which thins toward the margins of the sand blow, suggests that the ground surface subsided here during the first event and that silt and clay were deposited out of suspension from water that was ponded above the sand blow. The rate of deposition of the silty clay is not known. However, laminations within the deposit indicate that it accumulated slowly over time. Also, soil characteristics of the lower sand blow indicate that it was subjected to soil-forming processes prior to burial by the upper sand blow.

The presence of both late Woodland and early Mississippian artifacts within the buried occupation horizon suggests that the lower sand blow formed during the transition period between the two cultures, about A.D. 800 ± 100 yr. The development of a late Mississippian occupation horizon on the upper sand blow indicates that it formed prior to 1670. Radiocarbon dating of tree roots within cultural pits dug into the upper sand blow is consistent with this maximum age estimate. Therefore, the two sand blows formed between about A.D. 800 and 1670.

Liquefaction Features at Site Main-8

At Main-8 (Fig. 1), located ~12 km north-northwest of Blytheville, a complex liquefaction structure is composed of four sand dikes (numbered 1 to 4; Fig. 4). A clay layer at the base of the excavation is offset vertically by ~0.75 m and is crosscut by dikes 3 and 4, which are composed of pale brown (10 YR 6/3) medium to fine sand. The dikes contain clasts of surrounding units and clay carried up from below. Crosscutting relations between dikes 3 and 4 indicate two different liquefaction events, which may be related to individual earthquakes. Dike 4 extends to the top of the excavation, crosscutting all other sandy units above the clay, and therefore represents the most recent liquefaction event. Dike 4 shows almost no sign of soil development. Two of the sandy units that are cut by dike 4 also exhibit characteristics of liquefaction features, including intrusive contacts, flow structure, and clasts of surrounding units. These two units are interpreted as older sand dikes that represent two previous liquefaction events. The oldest dike (1) is a yellowish brown (10 YR 5/4) medium sand and is crosscut by a somewhat younger dike (2) of light brownish gray (10 YR 6/2) medium sand. Dike 1 contains slightly more (4% to 6%) clay than the other dikes.

From the youngest (4) to the oldest of the dikes (1), there is development of soil structure and consistency and a slight difference in color. The youngest dike is characterized by single-grain structure and loose consistency, whereas the oldest dike is characterized by moderate, fine, subangular blocky structure and very firm consistency. Higher clay content in the oldest dike may reflect the accumulation of clay over time due to weathering and translocation. The color of the oldest dike varies by 1 unit in both chroma and value from the youngest dike.

On the basis of crosscutting relations and soil development of the sand dikes, this complex structure may have formed as a result of three, possibly four large earthquakes, including an event in 1811 and 1812. Wood collected from the clay layer exposed at the base of the excavation yielded a radiocarbon age of 4930 ± 160 yr B.P. (Geochron-17728), which corresponds to a 1σ calibrated age range of 3940 to 3535 B.C. (2σ range of 4035 to 3360 B.C.). Because they either crosscut or stratigraphically overlie the clay layer, all of the liquefaction features at this site formed during the past 5–6 ka. Radiocarbon dates of additional samples collected above and below

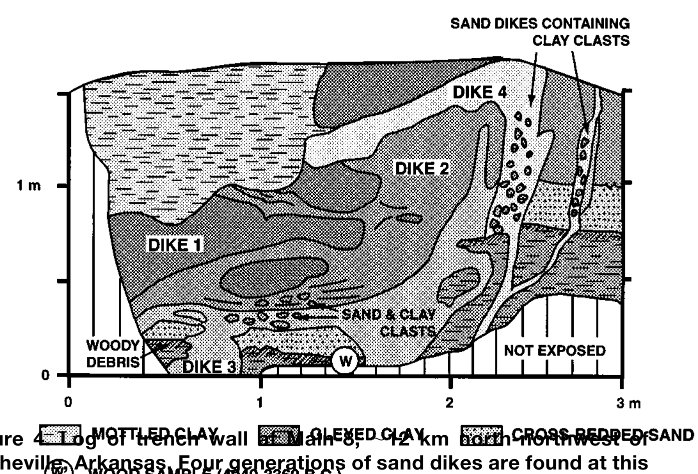

Figure 4. Log of trench wall at Main-8, ~12 km north-northwest of Blytheville, Arkansas. Four generations of sand dikes are found at this site. Youngest sand dike (4) exhibited almost no signs of soil development, suggesting that it formed during 1811 and 1812 earthquake sequence. Three older generations of liquefaction features exhibit soil characteristics indicative of more advanced age. These four generations of sand dikes formed since 4040 B.C.

the sand dikes are pending. Archeological artifacts were not available at this site to help determine the ages of the liquefaction features.

DISCUSSION AND CONCLUSIONS

Liquefaction features at three sites near Blytheville, Arkansas, indicate the occurrence of two, possibly three, prehistoric earthquakes in the past 5–6 ka. These features include (1) a sand-blow crater that formed between A.D. 800 and 1400, (2) two stacked sand blows that formed between A.D. 800 and 1670, and (3) two, possibly three, prehistoric sand dikes that formed since 4035 B.C. In addition to the features described here, we have observed other prehistoric sand blows in the region that are overlain by Native American occupation horizons or that exhibit soil characteristics indicative of a pre-1811 age (Fig. 1).

It is important to note that soil development in the paleoliquefaction features at Yarbro-304, Eaker-560, and Main-8 is subtle. Without the presence of the Native American occupation horizons and artifacts, or careful attention to soil characteristics, the paleoliquefaction features might have been mistaken for 1811 and 1812 features. This raises the possibility that some prehistoric liquefaction features in this area may have been misinterpreted as 1811 and 1812 features during previous studies. Wesnousky and Leffler (1992) and Rodbell and Schweig (1993) interpreted all liquefaction features that they observed as forming in 1811 and 1812. Neither of these studies had the benefit of Native American occupation horizons to help bracket the ages of liquefaction features, nor did they consider soil characteristics of sand blows. Our research shows that soil characteristics of late Holocene sand blows can help to differentiate episodes of liquefaction. We are documenting soil characteristics of sand blows of different ages in order to construct a regional soil-development index. This index may be useful in estimating the age of liquefaction features where other means are not applicable.

The prehistoric liquefaction features near Blytheville, Arkansas, suggest recurrence intervals of hundreds of years for large earthquakes capable of inducing liquefaction. This result is consistent with most other paleoseismological studies in the region (e.g., Russ, 1982; Saucier, 1991; Vaughn, 1991; Kelson et al., 1994). Short recurrence intervals might be expected given geodetic and seismological evidence for high strain rates in the seismic zone (Schweig and Ellis, 1994). The magnitudes of the earthquakes that generated the paleoliquefaction features near Blytheville are difficult to determine, especially with the limited data currently available. The prehistoric liquefaction features are similar in size to, if not larger than, features that formed during the 1811 and 1812 earthquake sequence. This suggests that the prehistoric events may have been great New Madrid–type earthquakes. Much work remains to estimate realistic magnitudes for these prehistoric earthquakes; however, mapping the age distribution of liquefaction features is an important first step.

Attention to archeological features and soil characteristics has led to the identification of prehistoric liquefaction features in an area where they had not been recognized previously. This interdisciplinary approach holds promise for the identification of many more prehistoric liquefaction features in the region and the development of a paleoearthquake chronology for the New Madrid seismic zone. Such a chronology will contribute to the assessment and mitigation of earthquake hazards in the central United States.

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